Experimental theoretical modelling of concrete shrinkage in massive structures

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Abstract. In spite of the high culture of modern construction, the majority of massive structures erected in different countries of the world cannot avoid shrinkage cracks during the curing process, which negatively affect both the stiffness and durability of such structures. Shrinkage processes in massive structures are not regulated by standards, although a large number of specialists deal with these issues. During design and construction of most massive structures (usually such structures are unique), separate special studies are carried out for each project, calculations of stress state are performed, and technological regulations are prepared, but the actual values of shrinkage deformations almost always differ from the calculated ones. The task of this study is to develop a methodology for measuring concrete shrinkage in massive structures, as well as to determine the qualitative criteria by which one or another shrinkage deformation can be estimated. The obtained results allow a more correct understanding of the stress-strain state that occurs in massive structures after pouring concrete mixture and more correctly prepare technological regulations, which will reduce the number of cracks in the poured structure.

Keywords: concrete, shrinkage, creep, relaxation, long-term testing

Introduction

The total shrinkage of concrete according to the European Concrete Institute (CEB No. 213/214) of 1993 and the research of the international laboratory RILEM (TC 107) of 1998 can be divided into 5 components:

- capillary or plastic shrinkage, which occurs in freshly placed concrete due to early water loss;
- chemical shrinkage, caused by the chemical reaction of cement and water;
- autogenous shrinkage, which in most cases is regarded as the sum of the components of chemical shrinkage (see above) and self-drying shrinkage resulting from internal drying due to the hydration process;
- drying shrinkage, caused by the loss of water from cured concrete in a dry environment;

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- carbonation shrinkage, which occurs due to carbonation of the surface zone of the concrete.

Autogenous shrinkage (conditionally internal shrinkage) and drying shrinkage (conditionally external shrinkage) have the greatest influence on total shrinkage, according to European studies. Each of these components has a different proportion of the total shrinkage, depending on various parameters. In addition to the many parameters of the concrete mixture and climatic conditions, the dimensions of the structure also have a major influence on the development of shrinkage. Conventionally, a construction type can be described as either massive or non-massive. Solid concrete structures are especially used in nuclear engineering and hydroelectric engineering, in the lower walls and columns of high-rise buildings. In spite of the high culture of modern construction, in the majority of solid structures erected all over the world shrinkage cracks cannot be avoided during the curing process which has a negative effect on both the stiffness and the durability of such structures.

The normative document in Russia that regulates the testing of concrete shrinkage is GOST 24544 [1]. The main foreign standards on methods of determination in the world are: ISO 1920-8 [2], BS EN 12390-16 [3], ASTM C157 [4], ASTM C596 [5], ASTM C1581 [6].

All of these documents cover the testing of standardised prism and cylinder specimens; the ASTM [5] describes the additional testing procedure for concrete rings. Shrinkage processes in solid structures are not regulated by any standard. In various countries, an extensive number of studies have been carried out by international experts on the various factors that influence the shrinkage behavior of concrete - from the mixing parameters to the computer simulation of the crack formation mechanics and the like [7-20], but at the same time research into the influence of the massing factor has not been conducted.

The task of the present research work was to develop methods of measuring concrete shrinkage in massive constructions as well as to determine qualitative criteria which can be used to classify this or that construction as massive.

The basic idea of the experiment consists in the fact that the shrinkage process is considered on the cut of a massive construction (column) in the form of a plate or a beam; the impact of the removed part of the construction is modeled by special boundary conditions. The closest model specimen to the massive structure in question is the cube specimen (Fig. 1.), but such tests are also extremely time-consuming and expensive, so they can only be implemented as control tests to verify data on slab specimens and beam specimens.

![Fig. 1. Principle scheme for selecting samples - cube, slab and girder when modelling a solid concrete structure](image-url)
The slab specimen is a quarter of a solid vertical structure (column or pylon) with all but two sides (the exposed surface of the column) waterproofed. The tests can be carried out either in fixed formwork on three sides (bottom and 2 side faces), the top face was waterproofed with a film, or without formwork, in which case two side faces and the top face are waterproofed additionally. The beam specimen is waterproofed on all sides except the exposed face. This is the simplest modeling method, but it takes into account the largest number of conditions at the same time.

The authors of this article have developed techniques for conducting such tests, produced experimental specimens and carried out numerical modelling of the results of the experiment.

Methods

Since the developed methodology for determining concrete shrinkage in massive structures is unique and no such experiments have been conducted before, two series of tests specimens were carried out before the main group of tests to determine the best parameters of the design of the tooling, systems for fixing indicators and taking readings, as well as waterproofing of the specimens.

The first test specimen had dimensions of 600×600×100 mm. Formwork plywood was used as a mould. A metal structure was separately constructed for the installation of devices to measure the shrinkage deformations along the thickness of the slab as well as the total shrinkage deformation along the length.

The slab under test was a quarter of a massive vertical structure (column or pylon) with waterproofing of all faces except the sides (exposed face of the column). The tests were carried out in permanent formwork on three sides (bottom and 2 side faces) the top face was waterproofed with a tape (Fig. 2). On this slab was worked out the technology of metal frame device around the specimen for fastening of clock-type indicators, which were used to measure the movements of various points of the sample, also on the surface was created a system of taking readings based on the principle of DEMEC points - on the test specimen two round marks (made of Invar) with a cone-shaped notch in the middle at a fixed distance are glued or installed during concreting, then a special device with a base corresponding to the specimen is leaned against them. Contact is made through special tapered feet to which the holes in the tags are reciprocal. One of the legs is movable, which allows measuring deformations within 3-5 mm relative to the exposed base. Measurements are made with an hour-type indicator with an accuracy of 0.001 mm. In the framework of this work on the sample plates were made markings in the form of a field with squares, the size of the squares was selected based on the required number of control points, as well as the size of the samples. In this work, it is necessary to arrange maximum number of points to determine the deformations in different parts of the sample, so each square was of size 100x100 mm.

Based on the test results, the design of the test bench was modified (stiffness was increased), the design of the metal frame around the specimen was modified, and boundary conditions were worked out (using fixed formwork along the closed ends of the specimen). Additional tests were carried out using formwork with screws in from below, on one side and completely without screws to determine the effect of these screws on shrinkage deformations and to further secure the specimen in the mould. The screws were used to prevent the plate from warping and to assess the effect of this process on the cleanliness of the experiment.
After conducting a series of preliminary experiments to determine the best design of the test rig for each type of specimen, the basic test scheme was finally approved - slab and cube specimens are tested without permanent formwork (only waterproofing, additionally a series of specimens are made with anchoring to the base with self-tapping screws to prevent plate bending from warping.

When testing the beam and slab specimens, specimens of different sizes were used to determine the massiveness factor:

We used plate specimens of dimensions 200×200×120 mm, 400×400×120 mm and 600×600×120 mm in quantity of 4 pcs for each size. The formwork plywood was used as a mould, which was dismantled on the side edges after the concrete had hardened a day later. The two side and top faces were coated with sprayed waterproofing. Two specimens of each series were fixed to the base with screw screws, and a metal frame was constructed to measure shrinkage deformations through the thickness of the slab, not connected to the specimen and with clock-type indicators. On the other two specimens’ clock-type indicators were installed on the side surface for fixing horizontal deformations, on the surface was additionally created a system of taking readings based on the principle of DEMEC points in the form of a field with squares of 100×100 mm.

The control sample-cube has two side faces free of waterproofing. On one free side face 6 clock-type indicators are installed in two rows: at the bottom of the sample and at the top. On the upper waterproofed face there are 5 clock-type indicators for measuring vertical deformations.

When testing the beam specimens, a series of specimens of different lengths were made: 100×100×600 mm, 100×100×100 mm, 100×100×140 mm.

In contrast to the testing of slab specimens, the testing of beams was carried out in permanent formwork on four faces of the specimen (bottom, two side faces and one end). This mode of testing modelled a more constrained condition of the test specimen relative to the slab specimens.

The specimen was anchored from one closed face with self-tapping screws screwed through the formwork plywood to control the shrinkage process (so that the shrinkage deformation of the concrete in the specimen in the longitudinal direction could be measured with a clock-type indicator installed only on one side. In addition, a 100×100×100 mm specimen was made, in which the anchoring was made along the entire bottom surface to

![Fig. 2. Test fitted specimen slab for shrinkage determination tests (by authors)](image)
evaluate its effect on the stress-strain state of the specimen, as well as to identify the processes of warping and rotation of the specimens inside the formwork during curing.

Fig. 3. Determination of longitudinal deformation on slab samples 200 400 and 600mm

Fig. 4. Determination of transverse strain on 400mm slab specimens and a cube reference specimen (by authors)

Fig. 5. Conducting concrete shrinkage tests on beam specimens (by authors)
**Results**

At the moment the tests are still ongoing, but based on the analysis of the first experimental data obtained and the numerical studies carried out, distinctive features of shrinkage depending on the size of specimens have already been identified. According to test results, it has been detected that deformation of samples with dimensions 600×600×120 mm is qualitatively different compared to samples 400×400×120 mm and 200×200×120 mm (graphical evaluation of the deformation of the upper edge is given on the example of a 600x600x120 specimen; –( Fig. 3,4). Thus, the factor of massiveness has been determined, i.e., in structures having dimensions greater than 1200 mm in cross-section, processes of concrete shrinkage proceed somewhat differently in relation to columns and pylons of smaller sizes The transverse deformations of the slab specimen are shown in Fig. 7. Similar results were obtained in the beam specimens (Fig. 8). Sensor number 4 measures shrinkage strains in the longitudinal direction, sensors numbered 1, 2 and 3 measure shrinkage strains in the transverse direction, with sensor number 1 being closer to the exposed surface of the specimen and sensor number 3 being closer to the non-waterproofed surface of the specimen beam.

![Analysis of shrinkage results on the surface of 600x600x120 mm slab samples (by authors)](image)

**Fig. 6**. Analysis of shrinkage results on the surface of 600x600x120 mm slab samples (by authors)
Discussion

During the experiment, samples 600×600×120 mm had both shrinkage and swelling deformations. Shrinkage deformations occurred closer to the open edge of the surface, whereas swelling deformations of the sample occurred in the completely closed part, i.e., at the furthest point from the open surface or the middle of the column. (The developed
algorithm for taking shrinkage strain readings along the specimen face is shown in Fig. 6, see Fig. 7 for the results).

Thus, it can be concluded that shrinkage in massive structures occurs unevenly along the thickness of the sample: in the centre of the sample, it is almost damped or the opposite process of swelling occurs, while at the open surface or at the edges of the column, uniform settling occurs, which leads to uneven shrinkage in the whole structure and the development of shrinkage cracks, with damping along the depth.

When analysing the deformations of the beam specimens along the length at the beginning of the test, shrinkage deformations in the transverse direction were recorded only at the outermost sensors, (at a distance of 5cm from the edge), at a distance of 25cm from the edge (the next sensor) only swelling deformations were registered (see graph for specimen 10x10x60 in Fig. 8). These results are valid for samples of different lengths.

The 600x600x600mm cube specimen, which was cast to verify the results, also showed swelling deformations at the fully insulated edge, while shrinkage deformations occurred at the open-surface faces.

Thus, it can be concluded from the test results of various sample sizes that shrinkage deformation in massive structures is related to mass transfer, which in turn triggers exactly opposite processes, such as swelling and shrinkage, simultaneously, so that standard prism and cylinder tests when testing for massive structures may not give quite correct results.

Based on the results of the experimental investigation, numerical calculations were carried out by the finite element method to numerically describe the shrinkage process, which also confirmed the swelling process (Fig.9).

![Fig. 9. Simulation of the shrinkage of a slab specimen by means of temperature loads (left) and cross-sectional deformation of the specimen according to the results of the calculation (right) (by authors)](image)

Conclusions

The authors have proposed and validated a methodology for long-term shrinkage testing of concrete specimens as applied to massive structures. Experimentally unique results confirming the process of swelling within a solid structure have been recorded experimentally. Analysis of the data obtained and numerical simulation show that swelling of the tested specimens in the transverse direction is not only due to usual transverse deformations and Poisson's coefficient, but is mostly caused by the phenomenon of mass transfer (moisture transfer) during curing. During curing, several such processes occur simultaneously - moisture transport outward with shrinkage and moisture transport deep into the specimen due to stresses near the exposed surface caused by shrinkage. The second of these processes causes swelling of the specimen. In a real structure, this will cause internal stresses in the concrete that will partially relax with time.
The results obtained show that the shrinkage processes of concrete in massive structures are clearly different from the results obtained from tests on standard small prism and cylinder specimens in accordance with regulations and allow a more correct understanding of the stress-strain state that occurs in massive structures after the concrete mixture has been poured and more correctly prepare technological regulations, which will reduce the number of cracks in the poured structure.

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